Development of a Highly Efficient and Accurate Wind-Wave Simulation Framework for Operational Data Assimilation

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LONG-TERM GOAL

This research aims at developing a highly efficient yet accurate computational framework for the simulation and prediction of wave and wind coupled motions with wave phases being resolved, which will lead to an advanced data assimilation tool to provide more comprehensive environmental input for naval applications. Our ultimate goal is to pave the way for developing an operational tool for the Navy to use for ocean-wave-atmosphere battlespace sensing and prediction with high resolution.

OBJECTIVES

The scientific and technical objectives of this research are to:

(1) use the detailed physics revealed in coupled wind-wave simulations to obtain a fundamental understanding of wave surface-layer processes, based on which physics-based advanced wave-layer models can be developed;

(2) adopt a highly accurate immersed boundary method to perform turbulence-wave simulation on fixed Cartesian grid to achieve superior computation efficiency; and

(3) use the developments in (1) and (2) to pave the way for the development of a computational framework for data assimilation with a focus on the reconstruction of wavefield and the retrieval of coherent flow structures from field measurements.

APPROACH

This research builds on the combined simulation of wind-wave interaction achieved in a fully dynamical, two-way coupling context. In the simulation, evolution of wavefield is simulated with an efficacious high-order spectral (HOS) method that captures all of the dynamically important nonlinear wave interaction processes. Large-eddy simulation (LES) is performed for the marine atmospheric boundary layer (MABL) in a direct, physical context with wave phases of the broadband wavefield being resolved.   In LES, fully resolving the boundary layer at the air-sea interface is prohibitively expensive. We use a wall-layer model to represent the momentum exchange between the flow in the outer layer and the small but dynamically important eddies in the inner layer. The extensive, high

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resolution data obtained from the coupled LES-HOS simulation provide a unique opportunity to develop, assess, and calibrate wave-layer models.

In this study, we will adopt the immersed boundary (IB) method for turbulence simulation near surface waves, with the constraints of the moving water surface represented by a body force through a discrete force method, which can capture the boundary precisely. We use large-scale high-performance computation on massively parallel computers. Our coupled LES-HOS code is parallelized using massage passing interface (MPI) based on domain decomposition. With the developments of wave-layer model and IB method for turbulence-wave interaction, the computational cost will be reduced significantly. The simulation capabilities developed in this study will be used for data assimilation with a focus on the retrieval of coherent flow structures and the reconstruction of wavefield based on measurements. The simulation results obtained in this study will be compared with and validated against field measurement data.

WORK COMPLETED

During the fiscal year of 2011, substantial progresses have been made in this project, including:

- Theoretical development and evaluation of sea-surface roughness parameterization.

- *A priori* and *a posteriori* tests of dynamic sea-surface roughness model.

- Testing and validation of the coupled wind-wave computational framework with the implementation of wall-layer model.

- Elucidation of swell-induced variation to the vertical structure of marine atmospheric boundary layer.

- Application of the coupled wind-wave computational framework to offshore wind-wave-structure interaction.

RESULTS

This study uses LES as a numerical tool for the study of wind field. To validate the accuracy of our LES code, we first simulate the wind over a stationary rough surface and compare our numerical result with the recent experimental data obtained from wind tunnel measurement by Chamorro & Porté-Agel (2010). Figure 1 shows the vertical profiles of mean wind velocity. We match our simulation parameters with the experimental condition, for which the friction velocity is 0.102 m/s and the surface roughness is 0.03 mm. Figure 1 shows that the current LES result agrees well with the experimental data.

The dependence of the flow structure of near-surface wind field on the characteristics of sea-surface wavefield is critically important to the modeling of marine atmospheric boundary layer. The interaction between wind and waves induces a wave-correlated velocity and pressure field in the near-surface region of wind. One particularly important phenomenon is the effect of swell on the wind field. Previous studies (e.g. Sullivan et al. 2008; Hanley & Belcher 2008) have found that under low wind condition (for a geostrophic wind of $u_g \leq 6$ m/s), the fast propagating swell can induce low-level jet to the near-surface wind field and drive the wind. For many naval applications, the speed of geostrophic wind of interest is usually higher (e.g. $u_g > 8$ m/s) and it interacts with the local wind-sea. Figure 2 shows our LES result of the vertical profile of mean wind velocity for a geostrophic wind of $u_g = 10$

m/s. The cases of wind over wind-sea with and without swell are compared. Figure 2 shows that in the high wind condition, the fast propagating swell also induces a low-level jet to the wind field, which clearly increases the wind velocity in the near-surface region.

Relatively short surface waves propagate at speeds slower than the local wind, and exert resistance to the wind. Their effect on the wind field is not resolved in LES and is modeled as subgrid-scale (SGS) sea-surface roughness. In our work, the SGS sea-surface roughness is modeled as $z_{0,\Delta}=z_{0,s}+\alpha_w\varepsilon_\Delta$, where $z_{0,s}$ is the roughness length for smooth surface and ε_Δ is the roughness length scale due to the SGS waves. The dimensionless model coefficient α_w is unknown and is determined dynamically by matching the total surface stresses at the grid scale Δ and a test-filtering scale $\gamma\Delta$, where $\gamma>1$ (usually equals to 1.5 or 2). The value of ε_Δ is modeled based on the characteristics of the SGS waves. Four models are adopted and tested in our study: (i) a RMS-height model; (ii) a steepness-dependent Charnock model; (iii) a wave-kinematics-dependent model; and (iv) a combined-kinematics-steepness model.

Figure 3 shows the result of *a priori* test for the dynamic sea-surface roughness models. The total surface stress at the grid and test-filter scales is plotted as a function of α_w. The value of α_w at the intersection between the curves of the two scales indicates the solution of the dynamic modeling procedure. Figure 3 indicates that the wave-kinematics-dependent model provides good result because the total stress at the intersection is close to the benchmark value. The RMS-height and steepness-dependent Charnock models show relatively poor result because of the lack of wave kinematics in the model concept. And the combined-kinematics-steepness model behaves poorly as it overestimates the wave effect.

Figure 4 shows the result of *a posteriori* test for the dynamic sea-surface roughness models. The vertical profiles of the mean wind velocity associated with the four roughness models are compared with the benchmark value from a high resolution LES with all of the wave modes resolved. It is found that the result from the wave-kinematics-dependent roughness model agrees well with the benchmark result. The RMS-height model overestimates the near-surface mean wind velocity because it underestimates the total surface stress (cf. figure 3); in contrast, the steepness-dependent Charnock model slightly underestimates the near surface mean wind velocity. The combined-kinematics-steepness model behaves poorly as it apparently underestimates the mean wind velocity. The *a posteriori* test result in figure 4 is consistent with the *a priori* test result in figure 3.

IMPACT/APPLICATION

This project addresses the basic physics of wave surface layer, which will lead to better understanding of turbulence-wave interaction dynamics. It is expected to improve simulation efficiency significantly, which will lead to a powerful computational capability for direct comparison between measurement and modeling and for data fusion in field experiments.

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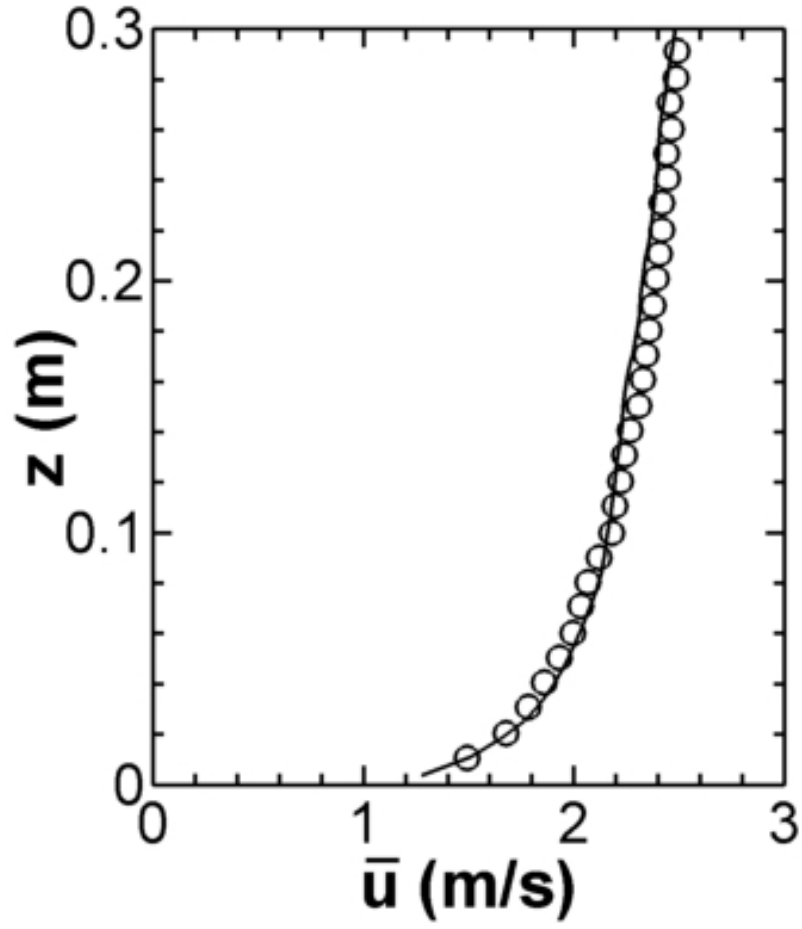
Figure 1. Comparison of the vertical profiles of mean velocity for wind over a flat rough surface: open circles, wind tunnel measurement data of Chamorro & Porté-Agel (2010); and solid line, current LES result. The friction velocity is 0.102 m/s and the surface roughness is 0.03mm.
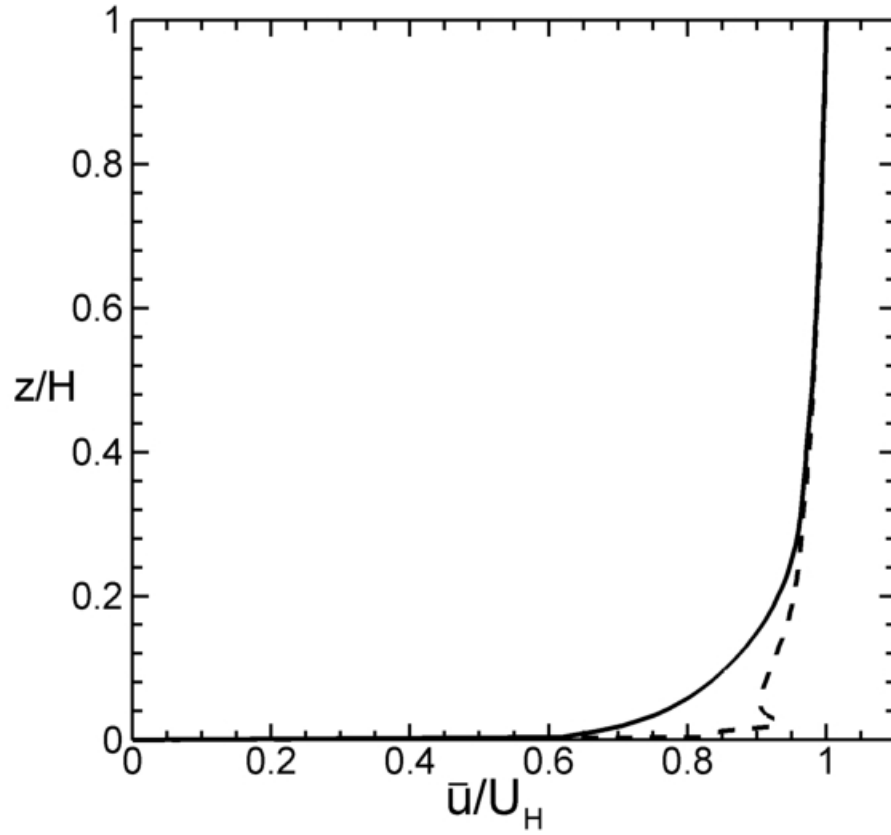
Figure 2. Effect of swell on the marine atmospheric boundary layer. Plotted are the profiles of mean velocity for wind over sea-surface wavefield: solid line, pure wind-sea; and dashed line, swell and wind-sea mixed wavefield. Here, the value of velocity is normalized by the mean wind velocity at the top of the simulation domain, z=H, where H=1km.
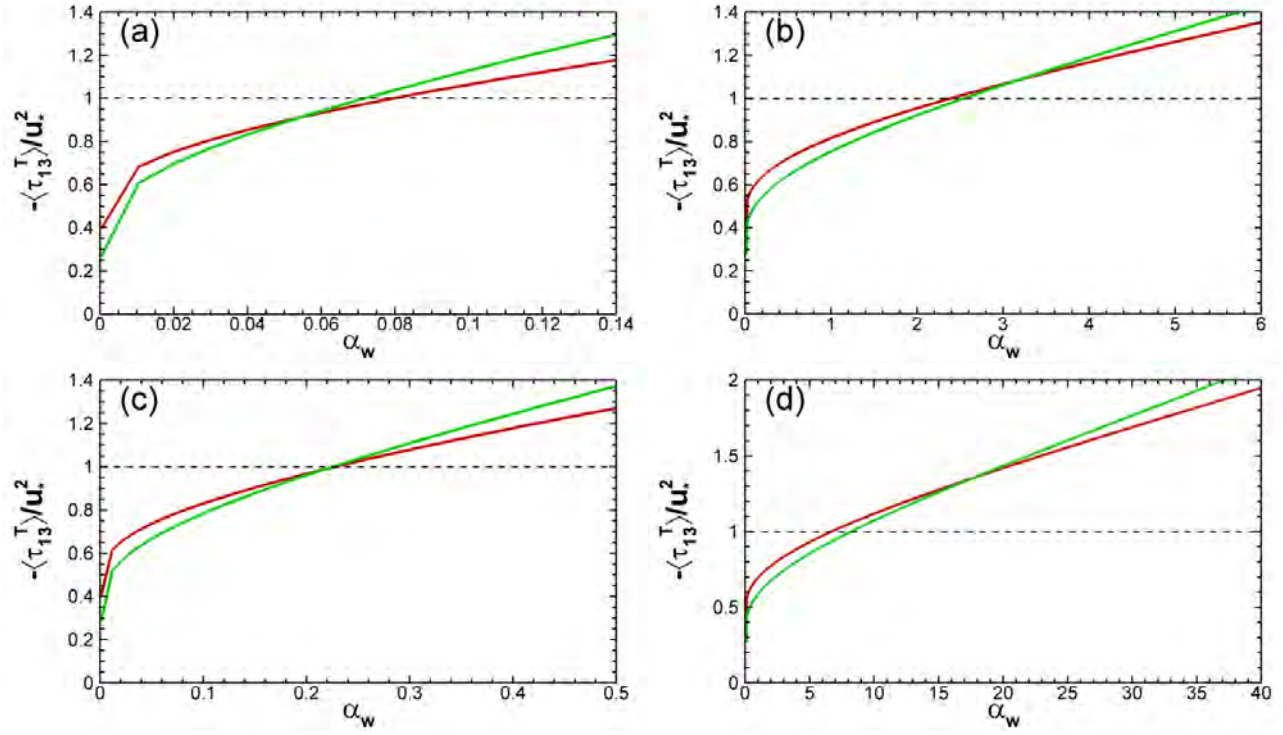
Figure 3. Result of a priori test of dynamic sea-surface roughness models. Plotted is the total surface stress as a function of roughness index α_w. The values of surface stress are normalized by u_*^2. Values corresponding to the grid scale Δ are indicated by red lines; values corresponding to the test-filter scale 1.5Δ are indicated by green lines. Four models for the subgrid-scale roughness length scale are tested: (a) a RMS-height model; (b) a steepness-dependent Charnock model; (c) a wave-kinematics-dependent model; and (d) a combined-kinematics-steepness model. The benchmark value of the total surface stress is indicated by black dashed line.
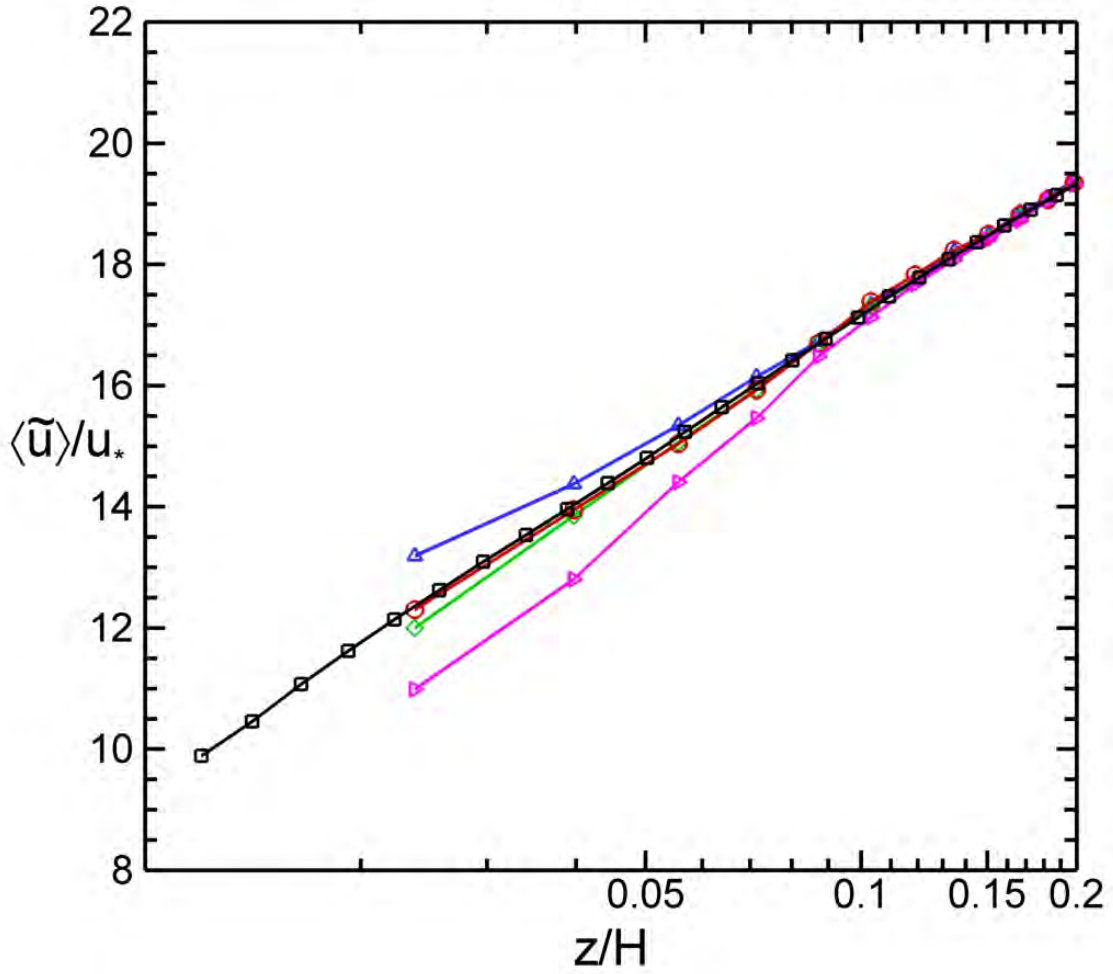
Figure 4. Result of a posteriori test of dynamic sea-surface roughness models. The vertical profiles of mean velocity are plotted in semi-logarithm scale. Results of four models for subgrid-scale roughness length are compared with the benchmark value obtained by a high resolution simulation: blue, a RMS-height model; green, a steepness-dependent Charnock model; red, a wave-kinematics-dependent model; magenta, a combined-kinematics-steepness model; and black, benchmark value.